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APPLICATION OF SMARTSHEAR TO DEFINE ROCK MASS SHEAR ABOUT COAL MINE ROADWAYS

**Benjamin Blacka¹, Stuart MacGregor², Adrian Rippon³,
Michael Melville⁴, Graham Wylie⁵, Anne Wylie⁶**

ABSTRACT: Shear movement of strata surrounding excavations is a critical factor in overall excavation stability. Understanding the location, timing, magnitude and direction of shear failure surrounding an excavation is useful for assessing primary and secondary roadway support requirements. A new routine shear monitoring instrument known as the SmartShear has been developed to accurately measure shear movement at multiple locations within a borehole. The shear movement is measured on a two dimensional plane at 90 degrees to the installation of the instrument using a series of tiltmeter sensors. Continual change in shear direction and magnitude over time is measured once the shear locations are detected.

This paper presents the findings from a field trial at Oaky North Mine, using the SmartShear system, assessing shear movement surrounding coal mine roadways. The timing and magnitude of shear movement along bedding planes and geological contacts has been measured during drirage of roadways. This paper is part of the ACARP project C25060.

INTRODUCTION

The successful introduction of routine roof deformation monitoring in the mid-late 1990's using Tell Tale based systems (MacGregor 1998), is now widespread in the Australian underground coal industry. The ability to routinely monitor ground behaviour about coal mine roadways enables the management of strata control hazards through the timely and systematic implementation of controls through the application of TARP based processes.

It is recognised that some modes of ground response are associated with little or no dilation of the rock mass. This can occur along discrete geological boundaries (shearing along claybands) and/or along localised failure surfaces through the rockmass.

The SmartShear is a cost effective, routine shear monitoring instrument that can easily be installed in open boreholes via a spring loaded mechanical anchoring system. The SmartShear is made up of a series of Micro Electrical Mechanical Systems (MEMS) tiltmeters that can be installed up to 10 m into open boreholes. Providing sufficient resolution to resolve discrete bedding plane shear and strata failure surfaces for the range of conditions present in Australian underground coal mines. The SmartShear instrument has been built as part of ACARP project C25060.

The ability to routinely monitor roadway failure mechanisms such as shear along weak interfaces has the potential to reduce the risk associated with these hazards. The nature of ground response associated with discrete shearing along planes of weakness (at depth into the roof, floor and ribsides) is typically not manifested in the same style or magnitude that failure of

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the intact rockmass presents. It is common for little or no visual or apparent warning to precede a fall associated with shear along discrete planes of weakness. Routine shear monitoring should address these failure modes and can be used in a supplementary fashion to traditional Tell Tale based monitoring to manage strata control hazards.

SHEAR FAILURE IN COAL MINES

Understanding the failure of rock mass and intact rock surrounding coal mine roadways is critical for roadway stability. The inherent variable nature of rock mass, as well as continual stress redistribution during mining, means that the strata surrounding roadways is considered a dynamic environment, which can lead to strata failure. Routine monitoring of all types of roadway deformation is important for maintaining a safe and productive mining environment.

Shear failure surrounding coal mine roadways can occur along bedding planes or intact rock. Unlike tensile/dilation based failure, shear failure can have little to no visual signs at the roadway roof/rib. Shear failure generally initiates in the corners of the roadway and can propagate further up into the roof, which can lead to large scale roof failure.

Shear failure of bedding planes in weak strata

Commonly in Australian coal mines, weak strata surround the coal seam. Extensive research completed during ACARP project C50232 at Springvale Coal Mine found that during excavation of a roadway as the stresses are redirected about the opening, if the shear strength of the bedding plane or geological contact is overcome, failure and slip along the interface will occur.

The slip along these interfaces can continue outside of the rib line and the effective span of the roadway is increased. This then leads to further redistribution of the stresses surrounding the roadway, which can increase shear failure further into the roof, and consequentially further out beyond the rib line, until an equilibrium is found. This process results in high angle shearing above the roof and beyond the ribline. During Longwall retreat, gate roads will undergo additional stress redistribution and this failure process is further exaggerated. Understanding the extent of shear failure is important, as the stability of the roadway and adjacent pillars can be compromised once the failure progresses upwards and outwards from the ribs, leading to increased effective roadway span and decreased effective pillar width.

Shear failure of intact rock

Shear failure of intact rock will occur once the failure criterion is met, as the stress acting on the rock overcomes the shear strength of the rock, leading to failure of the intact rock and lateral movement along the fracture (Gale 2018). As underground coal mining continues to progress deeper in Australian coal mines, the stresses surrounding roadways increase and therefore additional support and monitoring is required to overcome these additional stresses.

CURRENT STRATA MONITORING INSTRUMENTATION

Tell Tales

Currently the coal mining industry has an easy, reliable and affordable way to monitor dilation based roof deformation using Tell Tale extensometers. Multiple mechanically anchored roof extensometers are used extensively in coal mines throughout Australia. Tell Tales provide a continual visual indication of the roof conditions. They can resolve roof strata movement at up to four horizons. Tell Tales are typically installed in holes up to 10 m long for a range of hole sizes. They can be easily and quickly installed by operators on a systematic basis. (MacGregor 1998)

Tell Tales have been used in the industry for over twenty years and are considered an integral part of roadway monitoring and safety of workers underground. They are now an important part of coal mine Trigger Action Response Plans (TARPs) throughout the industry. Tell Tales are certainly an important instrument for routinely measuring dilation based deformation of a roadway, however they do not have the ability to measure shear displacement of the strata.

Traditional Shear Strips

Detailed underground based evaluation of shear along discrete interfaces has historically been achieved using strain gauge based shear strips as part of ACARP project (C50232). Shear strips have been used to accurately determine the location, timing, magnitude and sense of shear displacement at various Australian collieries. These are based on foil wire resistance strain gauges at close (50mm) intervals. Whilst successful at measuring high resolution of shear, they are limited to measuring shear in one dimension, have high manufacture costs and require grouting into position. This instrumentation is more suited to detailed field investigation and not for routine monitoring applications in underground coal mines.

SMARTSHEAR

The SmartShear is a cost effective, routine shear monitoring instrument for installation in ungrouted boreholes. The system is based on an existing MEMS sensor from Holville Pty Ltd that is certified (IECEX 12.0034X) Intrinsically Safe (IS) for use in Australian coal mines. A hand-held readout unit designed to be IS has been developed as well as an I.S. approved two wire Holville roofAlert™ communication and logging system.

The SmartShear instrument has been developed to accurately measure shear movement at multiple locations within a borehole. The shear movement is measured on a two dimensional plane at 90 degrees to the installation of the instrument using a series of MEMS tiltmeter sensors. Continual change in shear direction and magnitude over time is measured once the shear locations are detected. Figure 1 shows a schematic of the SmartShear system and the MEMS tiltmeter installed into a borehole undergoing shear movement.

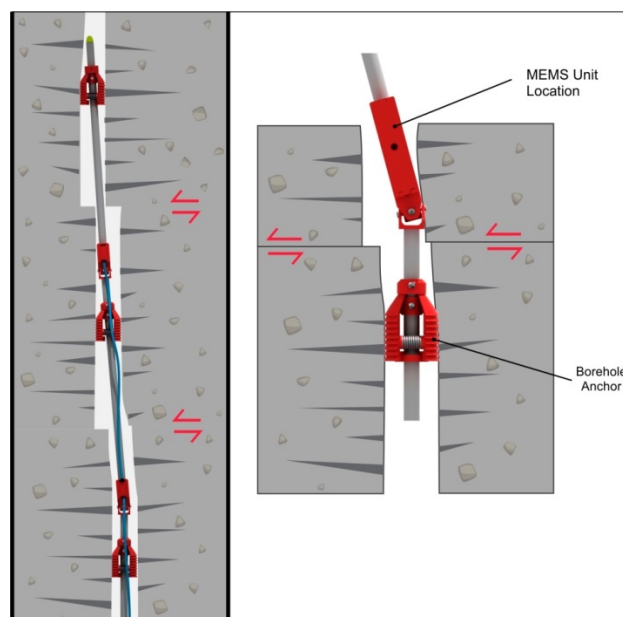


Figure 1: The SmartShear system including the MEMS tiltmeter, installed into a borehole undergoing shear movement

SMARTSHEAR DESIGN

The SmartShear instrument consists of a series of plastic lengths known as bay lengths that are coupled together, using plastic universal joints, with one side of the joint containing a MEMS tiltmeter. Attached to each bay length is a spring loaded, plastic anchoring system that when activated, enables the bay length to centralise in the borehole, anchoring itself to hold its position. A data cable runs down the length of the instrument, attached to a motherboard which is anchored to the base of the borehole. Figure 2 shows a final breakdown of the final design of the instrument and Figure 3 shows the anchor activation system.

The MEMS tiltmeter was developed by Holville Pty Ltd and has been designed to be integrated into the SmartShear at each bay length to detect shear movement at multiple horizons throughout the borehole. The MEMS tiltmeters are developed to be pre calibrated, so that the orientation of the borehole can be determined prior to any shear movement without the need of a base borehole reading.

An intrinsically safe hand held unit is used to download the data at the push of a button. The unit is designed to be reliable, easy to use and portable. The hand held unit is shown in Figure 4. The unit is able to download data from either wired or wireless versions of the shear monitoring device.

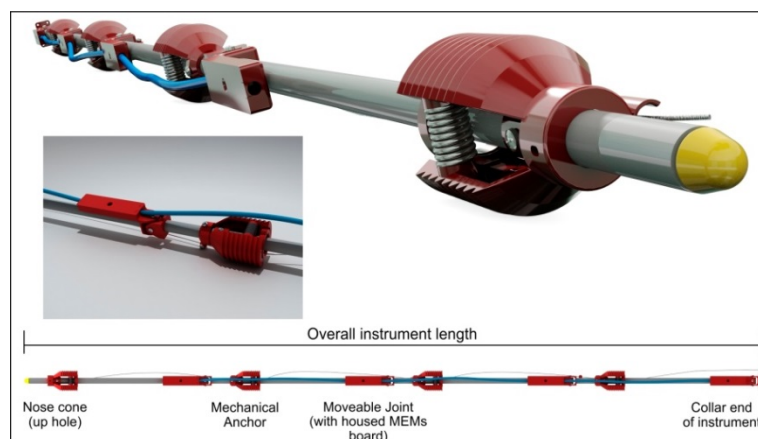


Figure 2: The SmartShear instrument, showing a breakdown of the main components.

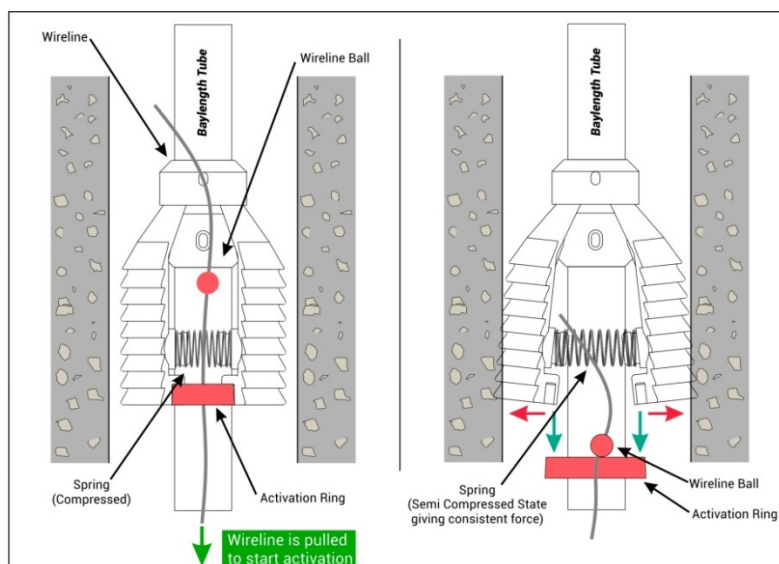


Figure 3: The activation and anchoring process.



Figure 4: Hand held readout unit

FIELD TRIAL – OAKY NORTH MINE

In March 2017 a successful field trial was undertaken at Oaky North Mine. The trial involved the installation of a 10 m long SmartShear with ten MEMS tiltmeters spaced 1 m apart. The instrumentation was installed during the drive of a longwall installation face as shown in Figure 5. The installation face was mined in two passes, with the instrumentation being installed after the first pass had been mined. After installation, shear monitoring readings were taken during widening, as the second pass was mined towards and then beyond the installation location. This provided a dynamic geotechnical environment suitable for field scale evaluation of the SmartShear and MEMS tiltmeter. The goal was to determine the location and magnitude of shear movement over time, as the second pass was mined. The effectiveness of the primary and secondary support could then be reviewed.

The SmartShear was installed so that any shear movement along the roadway was picked up as 'pitch' and any shear movement perpendicular to the roadway is picked up as 'roll'. The outcome of the trial showed:

- the 10 m long SmartShear was easily installed into a 60 mm borehole
- prior to engaging the anchors, the SmartShear was able to be rotated within the borehole and then secured at the base of the borehole to the desired orientation, i.e. MEMS tiltmeters facing both parallel and perpendicular to the roadway
- successful deployment of the anchors using the deployment wire
- all anchors successfully mechanically anchored without the requirement of additional adhesion i.e. cement or resin
- successfully took readings from the SmartShear using MEMS logger and laptop. (hand held unit not fully developed by this point)

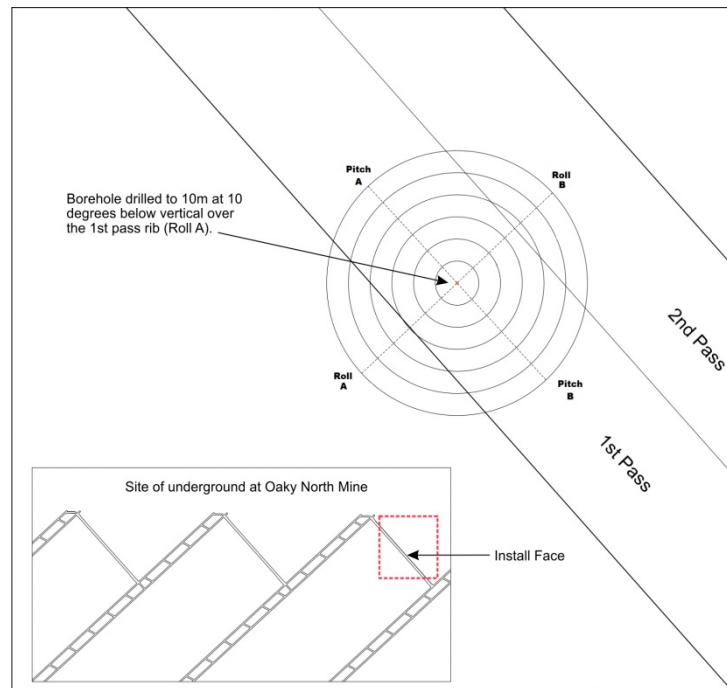


Figure 5: Plan view map of trial installation at Oaky North Mine, showing the installation location, the pitch and roll directions and the two mining passes

Oaky North Mine results

Figure 6 shows the cumulative displacement of the borehole relative to the end of the hole (as this is assumed to be the most stationary point) for both pitch and roll. The results show that the base of the borehole has moved inwards towards the second pass of mining, as shown by the positive 'roll' displacement. As the continuous miner mines towards the instrument location, there is a small amount of shear displacement in the lower two metres of the borehole. Once the miner mines past the installation site, the shear movement at the base of the borehole progresses further towards the second pass opening and shear horizons further up into the borehole begin to form. This trend of increasing shear movement and increasing height of shearing into the roof continues as the continuous miner mines further away from the site.

Figure 7 shows the horizontal displacement of each MEMS tiltmeters throughout the borehole relative to the above lying MEMS tiltmeter. This enables a good visual of the major shear horizons throughout the borehole.

The data can be plotted as a two dimensional plan view plot to represent the overall deviation change of the borehole from the base reading, as shown in Figure 8 referenced to the end of the borehole.

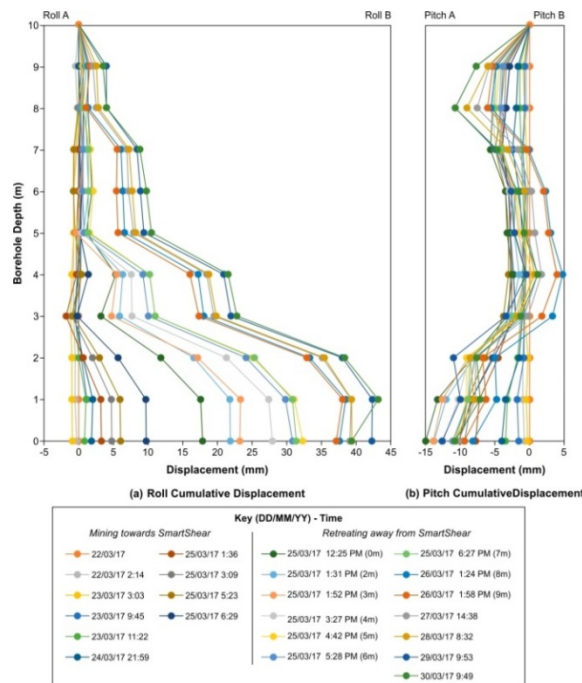


Figure 6: Cumulative displacement of the borehole relative to the end of the hole. tiltmeter.

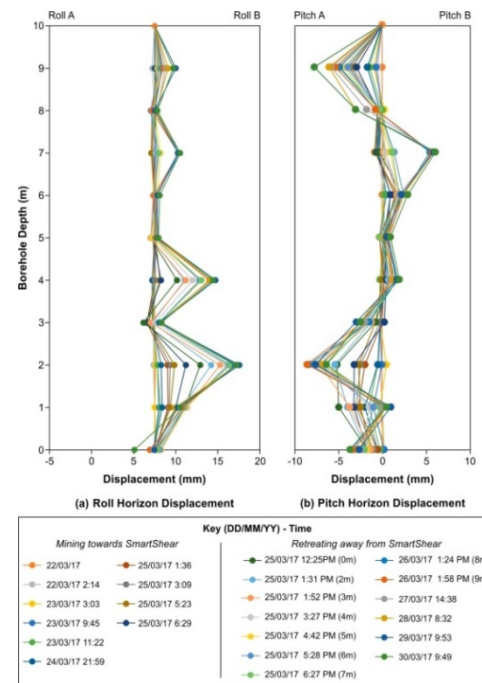


Figure 7: Horizontal displacement relative to the above lying tiltmeter.

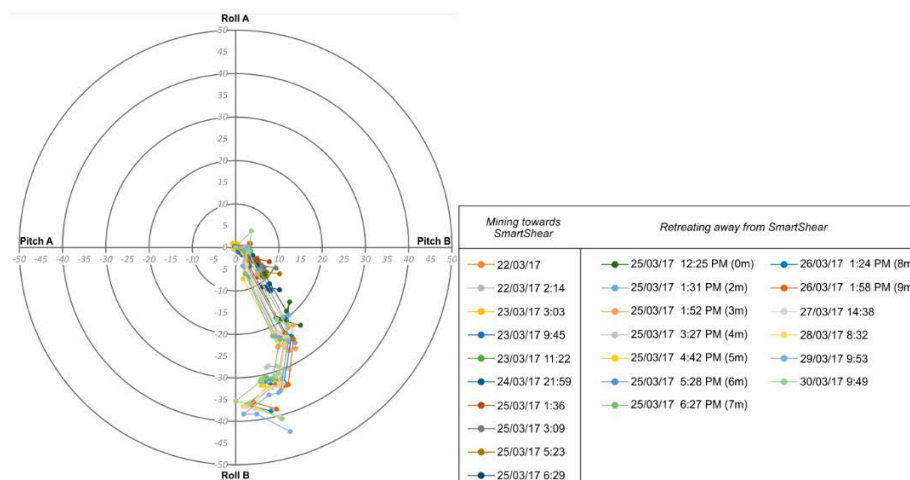


Figure 8: Plan view of overall deviation

APPLICATIONS FOR SMARTSHEAR IN UNDERGROUND COAL MINES

The SmartShear has a variety of applications to resolve rock mass shear for the range of conditions present in Australian underground coal mines.

Routine monitoring:

- Life of mine development areas
- Gate roads: Monitored over the life of the gate roads to assess the shear movement during different loading periods, i.e. during drivage and additional abutment loading from longwall retreat

Campaign monitoring:

- Installation faces
- Critical infrastructure
- Support optimisation
- Determine height of shearing
- Determine high angle shear zones beyond rib line

The SmartShear instrumentation has the potential to become an integral part of the underground TARPs system. With the ability to monitor the change in shear movement over time, a range of triggers can be set depending on the location of the SmartShear within the mine as well as the geotechnical environment of the area. This will provide early indication to mining officials and operators of changing geotechnical conditions, thereby allowing early remedial action to be taken to ensure roadway stability. Valuable information gained from the SmartShear system can then be used for future roadway and support designs.

The SmartShear is designed to connect to the roofAlert system. A real time monitoring system that links up the SmartShear as well as other geotechnical instruments. The data is sent live to the control room with total movement, georeferenced instruments and acceleration alarms, prompting actions that arise from pre-set triggers within the TARPS.

OTHER APPLICATIONS

Outside the coal mining industry the SmartShear has a number of other potential geotechnical applications as follows:

- Slope stability: SmartShear can aid in monitoring the stability of slopes in open pit mining environments, civil road cuttings and potential land slide locations. With the instruments ability to pick up early signs of movement, it can be monitored in real time and connected to an alert system.
- Underground hard rock mining environments: Stress environments that are continually changing as ore is extracted from the pit. SmartShear is useful for monitoring shear movement in roadways that will be affected by ongoing stress redistribution.
- Tunnelling: SmartShear can be utilised as part of routine monitoring in civil tunnels to ensure the ground support is adequately limiting shear movement surrounding the excavation.

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SHEAR STRENGTH OF ROCK JOINTS UNDER CONSTANT NORMAL LOADING CONDITIONS

Ali Mirzaghobanali^{1,2}, Faisal Alenezi¹, Peter Gregor¹, Naj Aziz^{1,2}, Kevin McDougall¹ and Andreas Helwig¹

ABSTRACT: The variation of shear strength of rock joints under constant normal loading conditions was studied. Three dimensional printing technology was incorporated to produce moulds of rock joints. Rock joints samples with three different roughness values were cast using concrete with uniaxial compressive strength of 20 MPa. Samples were sheared using a direct shear testing machine for normal stress values ranging from 0.25 to 0.7 MPa. In addition, effects of shear rate on shear strength properties of rock joints were experimentally investigated. It was found that the shear strength of rock joints is a function of normal stress, joint roughness and shear rate values. In addition, it was shown that three dimensional printing technology is a useful tool to replicate real rock joints.

INTRODUCTION

Joints in a rock mass have a significant effect on the shear strength and deformation properties of the rock. Lama (1978) investigated the mechanical behaviour of a rock mass and indicated that for closely spaced joints, the mechanical performance of the rock mass is similar to the mechanical behaviour of the joints. In the past, several researchers carried out tests to explore shear behaviour of rock joints. Patton (1966), Ladanyi and Archambault (1969), Barton (1973, 1976 and 1986), Hoek (1977, 1983 and 1990), Hoek and Brown (1985), Bandos *et al.*, (1981), Hencher (1989), Kulatilake (1993) and Saeb and Amadei (1992) performed research investigations on shear strength properties of both artificial and natural unfilled rock joints under Constant Normal Load (CNL) condition where dilation is not restricted during shearing.

Real rock joints have three dimensional roughness distributions which cannot be accurately simulated by artificial triangular or sinusoidal rock joints. In this context, Mirzaghobanali *et al.*, (2014) suggested that research studies on shear behaviour of rock joints should be carried out on real rock joints. Nevertheless, real rock joints with the same surface roughness value are rarely to be found in nature, thus, experiments repeatability is a challenge for researchers.

This paper describes experimental investigations into shear strength properties of joints cast using moulds of real rock joints for various normal stress and shear rate values under CNL conditions. Three dimensional printing technologies were incorporated to prepare moulds of real rock joints, facilitating shear test repeatability.

SAMPLE PREPARATION

Three moulds with different roughness values were prepared for this experiment. They were named as: 1R, 2R and 3R. As shown in Figure 1, moulds were made in pair using a blue material, incorporating three dimensional printing technologies as per direct shear testing machine specifications. Subsequently, a concrete mixture was produced and added inside the PVC moulds as shown in Figure 2(a). Once samples dried, they were taken out from moulds and left undisturbed for 28 days. Cylindrical samples were prepared using the same mixture for Uniaxial Compressive Strength (UCS) determination. USC was found to be 20 MPa after 28

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days. Figure 2(b) shows one of the prepared samples. All samples had the same cross sectional diameter of 63.4 mm. This diameter was used to calculate the cross sectional area of the samples and for the shear and normal stress calculations. At the final stages, the pair of samples were positioned on each other to be placed in the shear testing machine which exerted different normal loads of 750 N, 1250 N, 1750 N and 2200 N.

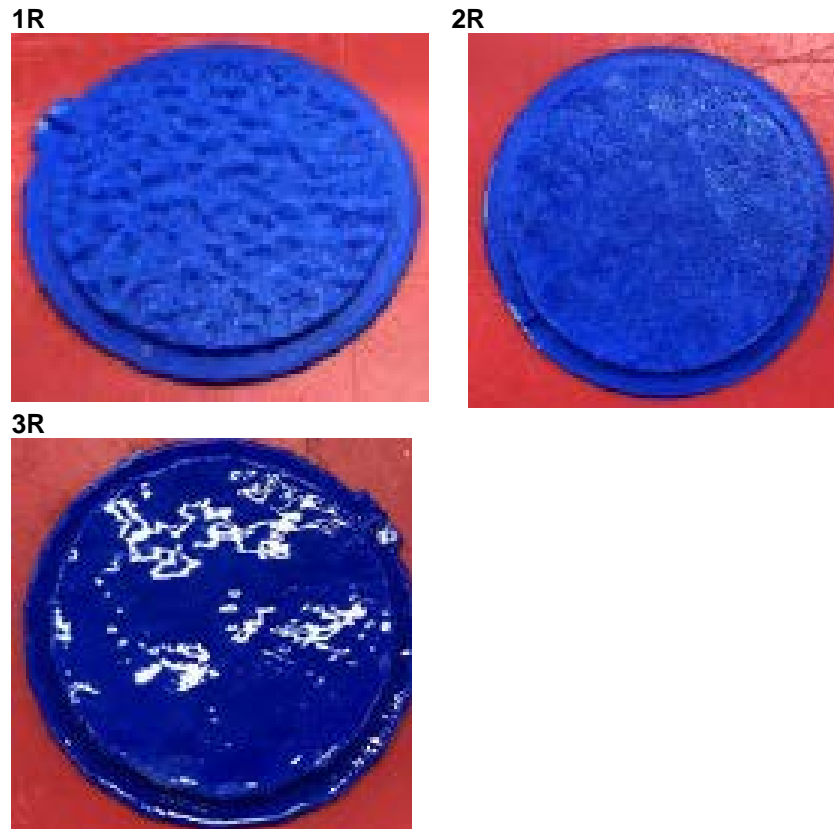


Figure 1: Moulds of rock joints prepared using three dimensional printing technology

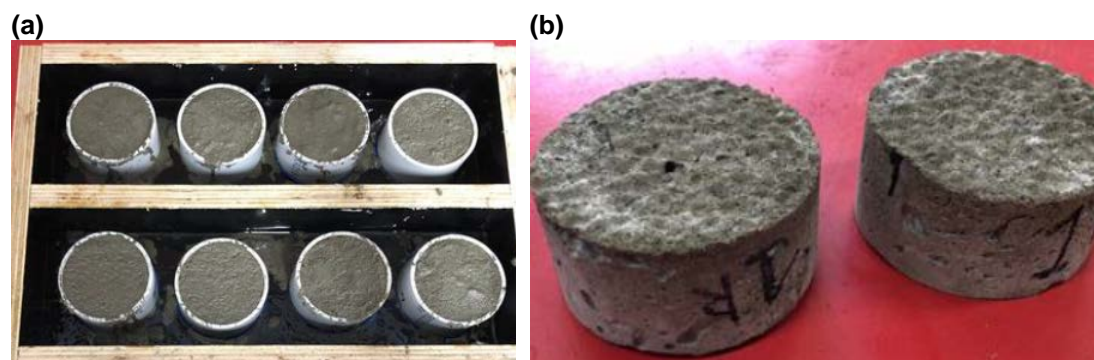


Figure 2: (a) Sample preparation procedure (b) prepared sample based on R1 mould

TESTING PROCEDURE

The testing machine which was used to apply the shear and normal load on the samples is ShearTrac ii as shown in Figure 3. This is an automatic loading system which includes transducers. The amount of load which this machine applies on the testing samples is controlled based on the feedback from these transducers. This machine is equipped with the sensors of two force transducers (normal and shear) and two transducers for horizontal and vertical displacement.

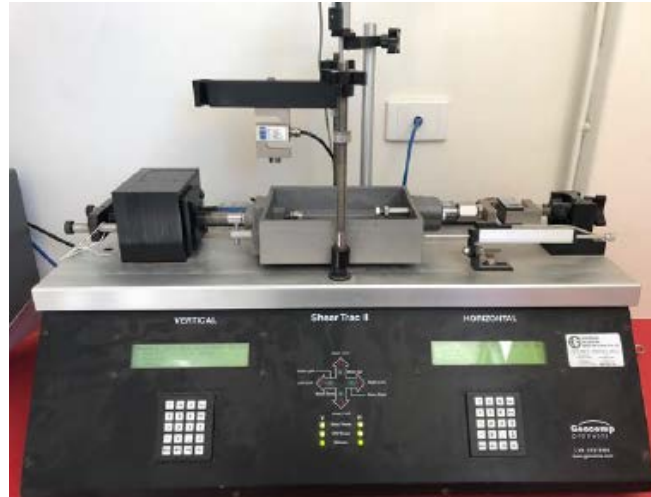


Figure 3: Fully automated direct shear testing machine

The system is connected to a computer to monitor the amount of load which is exerted to the samples. The computer loads or unloads the loading frame until the amount of loading which is read by the transducers becomes equal to the values required for testing the samples. Two-step motors connected to the gearing systems provide the normal and shear loads. They enable the loading mechanism to be raised and lowered for exerting the normal load and to be moved left and right for applying the shear load.

Each pair of samples was held together and mounted on the shear box in the testing machine. After calibrating the vertical and horizontal position of the sample with the normal and shear loading arms, the vertical load was set to a fixed value since the test was performed under constant normal load of 750 N, 1250 N, 1750 N and 2200 N. In the next step, the shear or horizontal load was applied and increased until the upper part of the sample slid over its lower part. It should be mentioned that the shear load was applied at a rate of 2 mm per minute for part (A) of the testing campaign.

The values of both normal and shear load and dilation results were displayed on the computer monitor during the test. This procedure was repeated for all samples under the specified loads. Shear and normal displacements were measured by the transducers and the experimental data was saved on the computer. Figure 4 indicates samples 2R when it is under a constant normal loading of 1250 N within the testing machine.

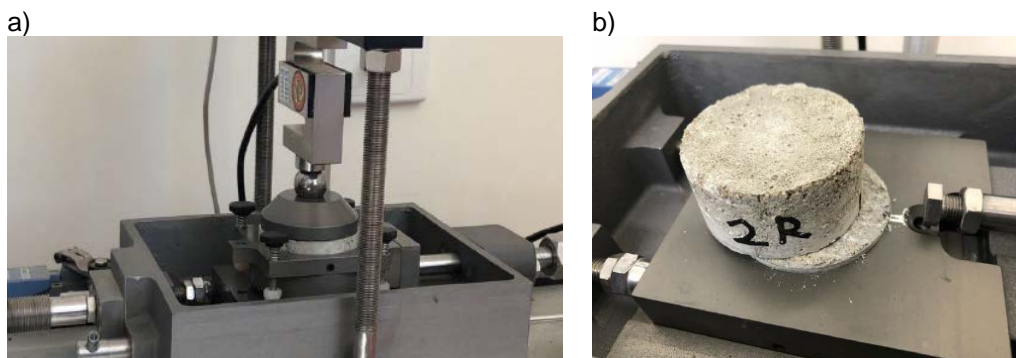


Figure 4: a) sample 2R during testing b) sample 2R after testing

RESULTS AND DISCUSSIONS – PART (A)

Each sample was tested with different loads and results are presented in three plots: normal stress, shear stress and dilation curve. These plots are based on the variation of shear displacement. As observed in the plots, normal loads which are constant for all samples are 2200 N, 1750 N, 1250 N and 750 N. In terms of the magnitude of the normal stress on the samples, load 2200 N applies a normal stress of 0.7 MPa, load 1750 N yields a normal stress of 0.55 MPa, load 1250 N a normal stress of 0.4 MPa and then the normal stress of 0.25 MPa. Shear load and stress values for samples are different due to differences in the roughness of samples. Figures 5 to 7 are the results of this test for each sample.

As shown in Figures 5 to 7, the shear stress curves first reach to their peak values with an almost linear trend and then remain almost constant as the residual stress by increasing the shear displacement. It is clear, the peak of shear stress increases with increasing the normal stress. It means, for example in the sample 1R, the peak of shear stress for 0.25 MPa normal stress is around 0.15 MPa while it is around 0.45 MPa for the normal stress of 0.7 MPa. This trend can be also observed for other samples.

Roughness of samples affects the location on which each curve reaches the peak of shear stress. For instance, for sample 1R, the peak of shear stress for different loads happens at the shear displacement of around 1.8 mm while this value decreases for samples 2R and 3R. For the same value of normal stress, it is clear that the value of roughness in different samples also affects the peak value of shear stress.

In a general trend, dilation increases with the reduction of normal stress. In other words, highest vertical load of normal stress on each sample leads to the lowest value of dilation and vice versa. However, there are some exceptions in the plots which can be due to experimental error. Negative values for dilation curves on particular shear displacement locations for some loads means the compression during the shearing load on that location and the slope direction of the rock joint is negative at those particular shear displacements.

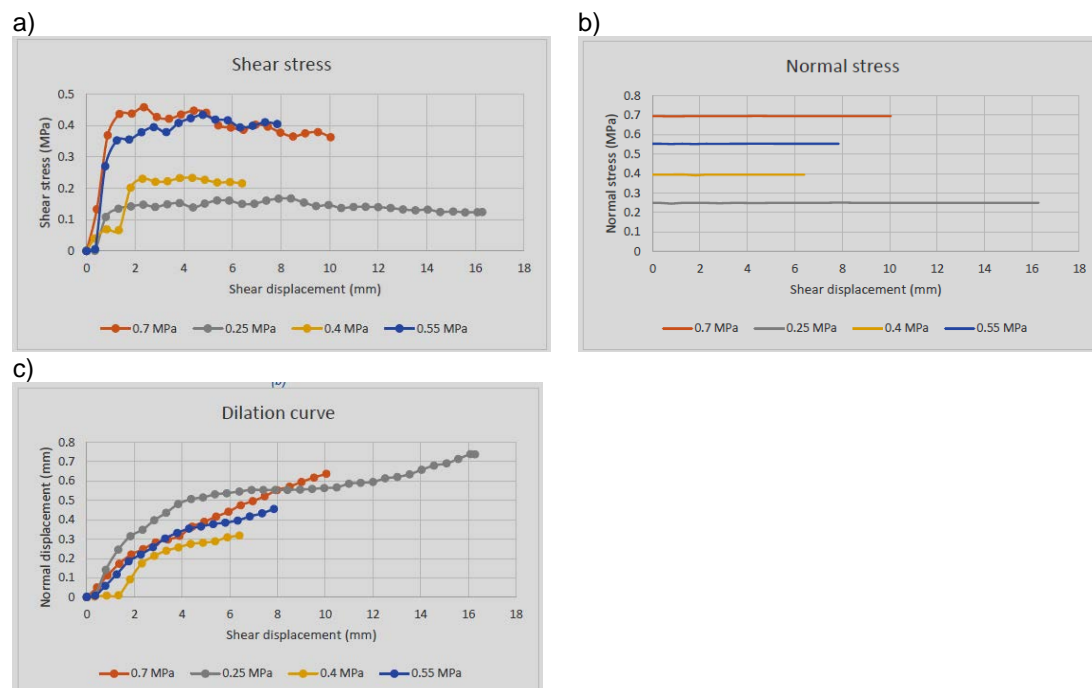


Figure 5: Experimental results for mould 1R a) shear stress versus shear displacement b) normal stress versus shear displacement c) dilation versus shear displacement

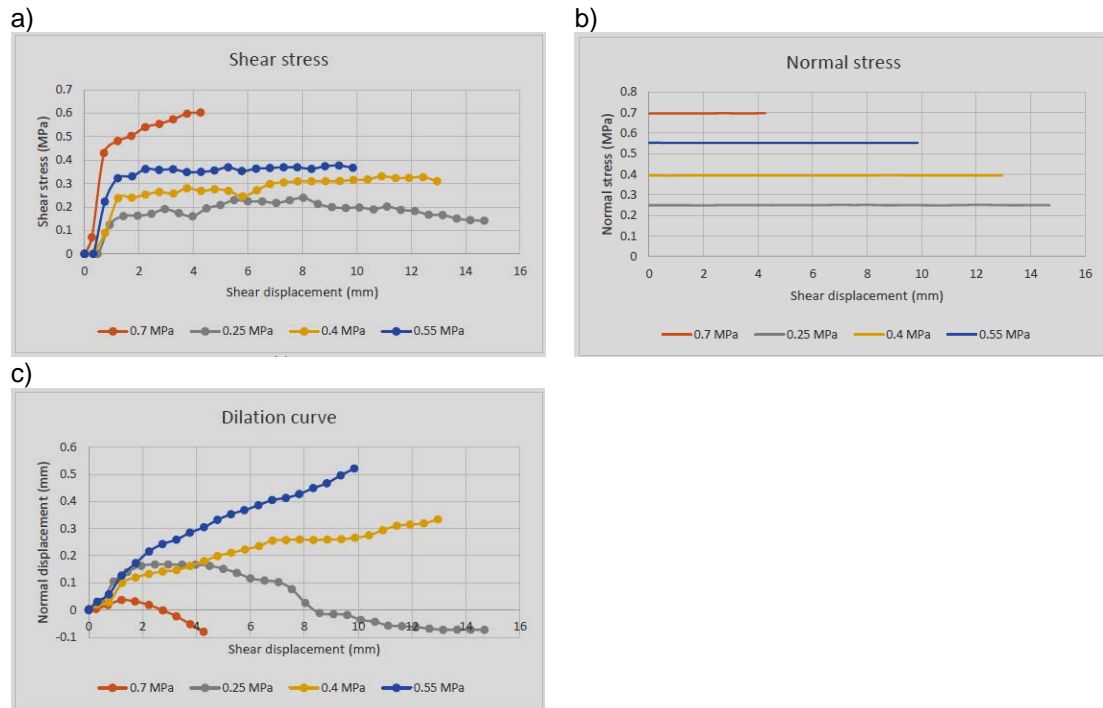


Figure 6: Experimental results for mould 2R a) shear stress versus shear displacement b) normal stress versus shear displacement c) dilation versus shear displacement

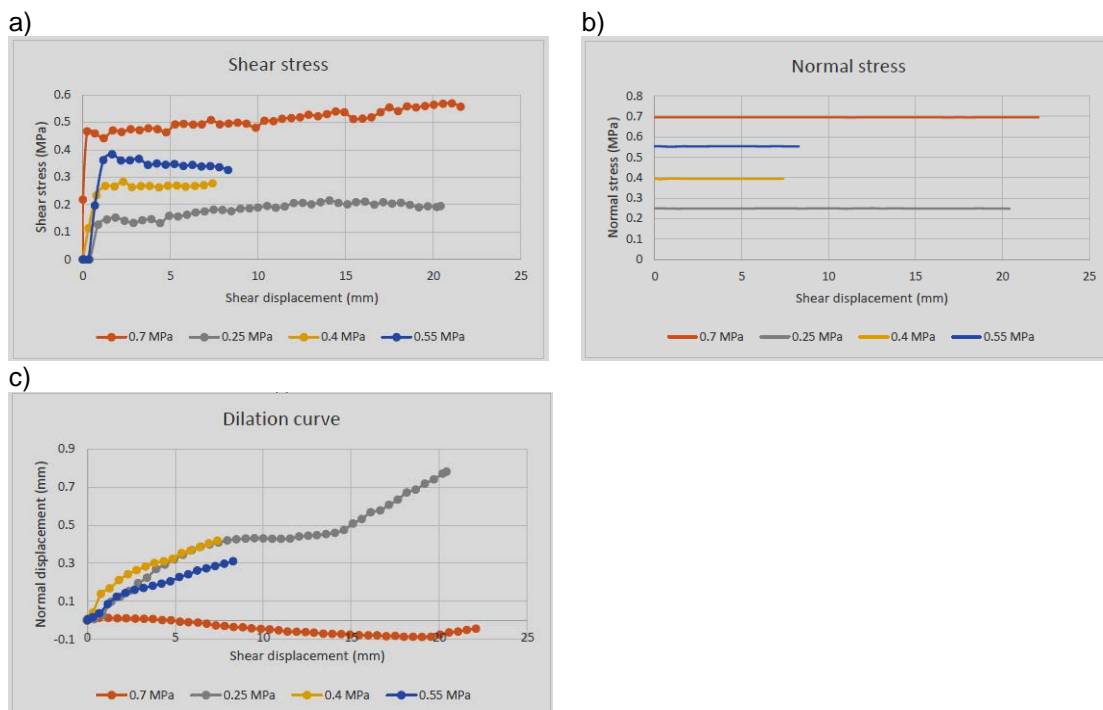


Figure 7: Experimental results for mould 3R a) shear stress versus shear displacement b) normal stress versus shear displacement c) dilation versus shear displacement

RESULTS AND DISCUSSIONS – PART (B)

The above results were obtained with the shear rate of 2 mm per minute. In a different test series, two moulds of 1R and 3R were selected for the experiment. The same testing procedure was applied on samples cast using these two moulds with the normal load of 1750 N but shear

rate of 0.5 mm per minute and 1 mm per minute. The purpose was to investigate the effects of shear rate value on the shear stress, normal stress and dilation curve. The plots presented in Figures 8 and 9 are the results of these tests. They compare the results for samples 1R and 3R for different shear rates of 0.5 mm per minute, 1 mm/min with the previous results for these samples with a shear rate of 2 mm /min.

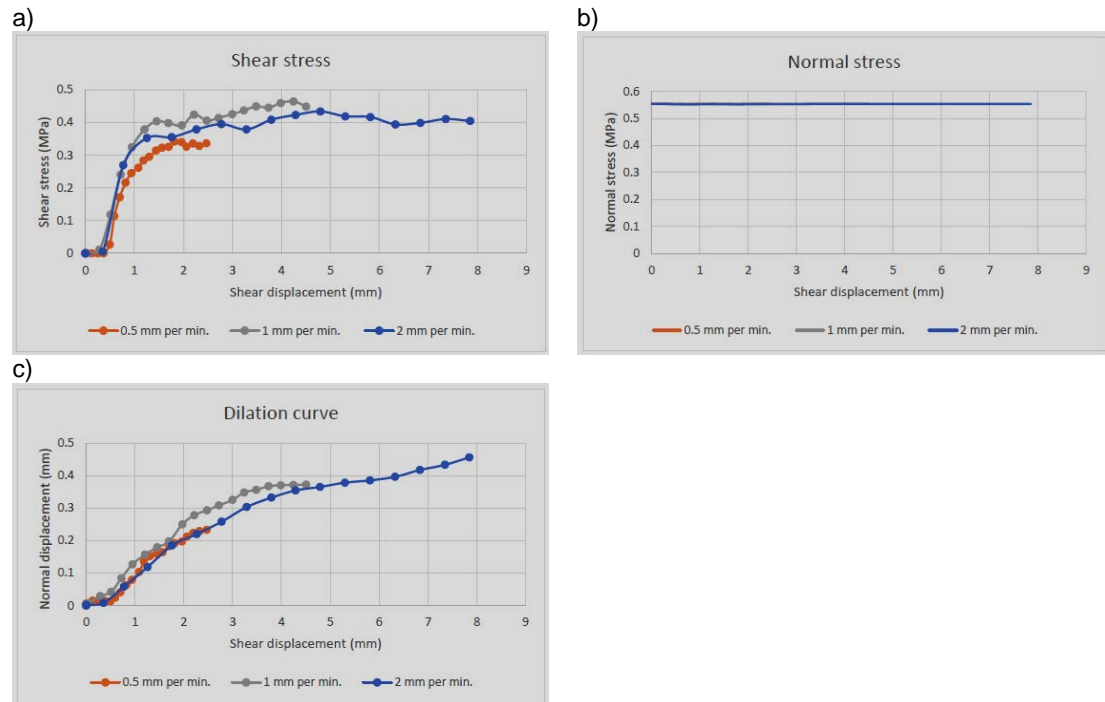


Figure 8: Experimental results for mould 1R with various shear rate values a) shear stress versus shear displacement b) normal stress versus shear displacement c) dilation versus shear displacement

As indicated in Figures 8(a) and 9(a) for the shear stress versus shear displacement plot, the shear rate affects the behaviour of shear stress curve against shear displacement. Usually the peak value of shear stress increases with increasing shear rate. As the shear rate increases, the frictional resistance which is presented by the joint surface becomes larger which causes the increasing shear strength of the joint.

For the shear rate of 0.5 mm per minute, the curve first increase rapidly and then remains nearly stable at the shear stress of around 0.35 MPa. This trend for the shear rate of 1 mm per minute is similar with the difference that the curve remains nearly constant at a higher shear displacement which is due to a higher shear rate. The peak value of shear stress at this rate is 0.48 MPa. For the 2 mm per minute shear rate, the curve experiences a higher shear displacement but its peak shear stress of around 0.43 MPa is slightly less than that for the 1 mm per minute.

Figures 8 and 9 (b) present the plot of normal stress against shear displacement for different shear rates. It is clear, all curves are flat with no change in normal stress which indicated that the tests were performed under a constant normal load. There is no change in the value of normal stress at different shear rates because all experiments were carried out under the same normal load of 1750 N which applies a constant normal stress of 0.55 MPa on the samples.

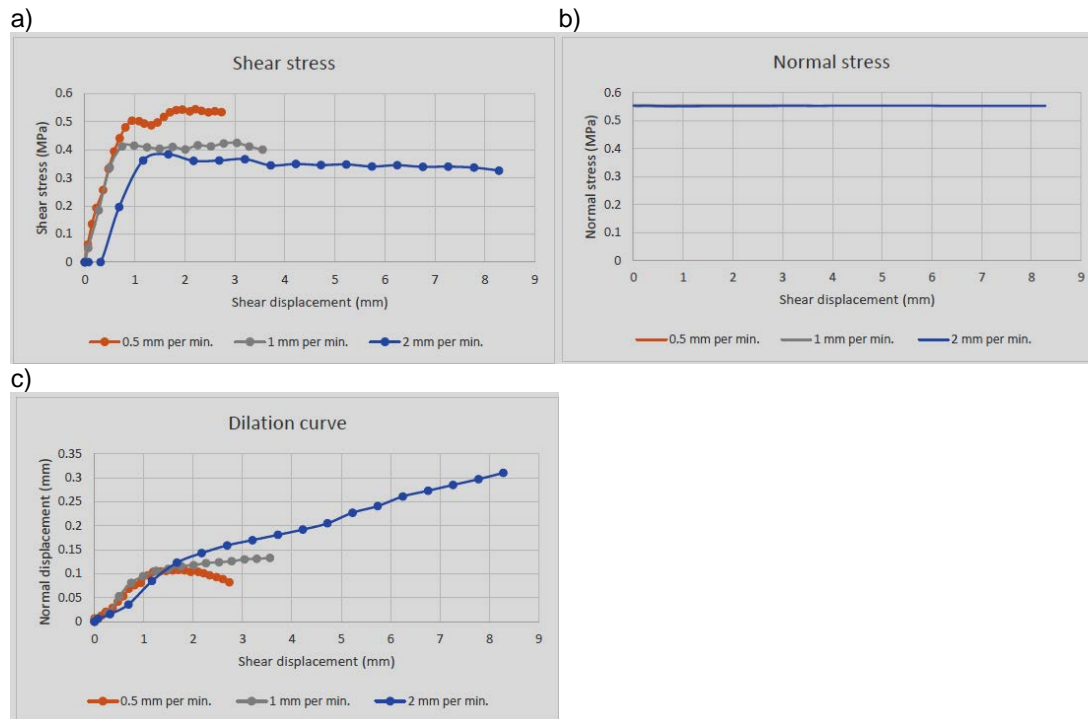


Figure 9: Experimental results for mould 3R with various shear rate values a) shear stress versus shear displacement b) normal stress versus shear displacement c) dilation versus shear displacement

Dilation curves are presented in Figures 8(c) and 9 (c) which is the plot of normal displacement against shear or horizontal displacement. It is obvious that all curves have an increasing trend along with the increasing shear displacement. For the shear rate of 0.5 mm per minute, the curve reaches a normal displacement (dilation) of 0.22 mm in the shear displacement of 2.7 mm. The curve related to 1 mm per minute shear rate experiences a peak normal displacement of 0.37 mm in shear displacement of 4.5 mm. For the shear rate of 2 mm per minute, the curve reached a normal displacement of 0.46 mm in a shear displacement of 7.9 mm. As a general trend for this plot, it can be said that the dilation increases with increasing shear rate.

CONCLUSIONS

The aim of this research work was to investigate the effects of roughness, normal stress and shear rate on the unfilled joint shear behaviour under constant normal load condition. Three pair of moulds with different roughness was prepared to be used in shear testing machine. Four different normal loads were selected and were applied on the samples individually. This experiment was performed in two phases. At the first stage, each pair of sample was placed on the testing machine and was applied under a constant normal load and varying shear load. The shear rate was 2 mm per minute in this phase. This process was repeated 4 times. For the next phase of this experimental work, two of samples were selected for a different experiment. The testing process was almost similar to the first phase with the difference that this stage was carried out only for one normal load and two different shear rates of 0.5 mm per minute and 1 mm per minute. Following conclusions can be made from this experiment:

- The peak shear stress increases with increasing normal stress,
- Roughness value affects the location of the peak shear stress,
- The peak shear stress increases with the increase of the joint roughness,
- Dilation increases with the decrease of normal stress,

- The peak value of shear stress increases with the increase of shear rate,
- Dilation increased with increased in shear rate, and
- The peak dilation decreased with reduction of roughness.

In addition, it was shown that three dimensional printing technology is a useful tool in studying shear behaviour of real rock joints.

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